Mechanical properties of warm-mix asphalt concrete containing different additives and recycled asphalt as constituents applied in real production conditions

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HIGHLIGHTS

- WMA with 35% of RAP and a mix additive of wax combined with fibres is a satisfactory material.
- The studied WMA blends revealed lower water sensitivity.
- Unlike WMA without RAP, stiffness of blends with RAP showed high sensitivity to porosity.
- Wax and cellulosic fibres increased resistance to rutting as compared to WMA with chemical additive.
- Production of WMA with a high RAP percentage is feasible by applying conventional means.

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ABSTRACT

This paper compares several warm-mix asphalt (WMA) blends and hot mix asphalt (HMA) in terms of their resistance to permanent deformation (wheel-tracking tests), fatigue performance and stiffness modulus (four-point bending tests), and water sensitivity (indirect tensile strength ratio). The first stage of the study included the production of Marshall specimens in laboratory to evaluate stability and flow of the blends’ specimens as well as their volumetric properties, aiming to select the most promising to apply in the field. WMA technologies involved the addition of four different products: a chemical surfactant, an organic wax, a chemical surfactant combined with cellulosic fibres and organic wax embedded in cellulosic fibres. One WMA blend incorporated 35% of reclaimed asphalt pavement (RAP). The second stage of the project involved the construction of trial sections in the field with plant-produced mixtures, laid and compacted with conventional equipment. Laboratory performance testing was carried out on specimens collected from the trial sections. The results showed that the level of mechanical performance of WMA was, globally, satisfactory and similar to the obtained for the HMA used as reference. Nevertheless, the warm-mix with surfactant additive revealed high sensitivity to temperature. The blend with RAP suffered some influence from the variation of binder quantity added by the RAP. The construction process in real production conditions proved to be feasible.

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1. Introduction

Warm-mix asphalt (WMA) are asphalt mixtures produced and compacted at lower temperatures compared to hot bituminous mixtures (HMA). Generally, they are produced in a temperature range from 100 to 140 °C [1,2], while hot asphalt concrete needs production temperatures above 150 °C. There are a number of available technologies to fabricate WMA, which are described with more detail elsewhere [3].

The easiest way of producing WMA is by adding some additives to the blend. Organic waxes, for instance, change some bitumen properties, such as viscosity. When the mixture includes surfactants as additives, they act at the interface between the aggregates and bitumen, decreasing friction at that interface and hence allowing lower temperatures to mix and compact a WMA. There are also
foamed bitumen techniques, which involve adding water into the mixture in different ways to improve its workability temporarily [3].

Although WMA generally show satisfactory mechanical performance, there are some documented weaknesses referred to in the literature and summarised below.

Since the aggregates are sometimes not completely dry before contacting with the binder, the moisture left behind can contribute to increase the water sensitivity of WMA. Therefore, the use of anti-strip additives [4] and/or increasing slightly the production temperature [5] can be applied as a technique to improve water sensitivity of WMA.

Manufacturing temperatures of WMA are usually around 120 °C. As a consequence, several authors have reported a decreasing in stiffness modulus as compared to the values measured for similar reference mixtures produced at higher temperatures [5,6]. Jenkins et al. [7] have reported a reduction between 40 and 60% and Sanchez-Alonso et al. [5] have found a decrease in a range from 10 to 50%, depending on the additive applied.

Although the literature reports that WMA have satisfactory fatigue behaviour, it also reports lower resistance of WMA to fatigue cracking at lower strain levels and intermediate temperatures (around 20 °C) than hot mix asphalt (HMA) [8]. Nevertheless, WMA seems to be less sensitive to the tensile strain level [9].

The literature [10,11] also indicates that WMA generally show good performance regarding low temperature cracking for all the types of technology applied to reduce production temperature. In terms of resistance to permanent deformation, WMA produced with wax additives tend to have enhanced resistance, as the additives change the in-service rheology of the binder [12,13]. However, since there is in general less stiffening of the binder during the mixing and compaction procedures, WMA show generally worse performance than the HMA used as reference, particularly when foam technologies are used [14].

The incorporation of RAP into HMA generally contributes to increase stiffness and reduce workability of the mix because the recycled binder is aged and consequently stiffer than the virgin one [15]. In the case of WMA, it can be anticipated that this problem will be lower because the production procedure is carried out at lower temperatures and, therefore, the binder’s aging will be lower than for HMA. Also some additives, such as organic waxes, can improve workability by reducing the bitumen’s viscosity [16].

Considering that performance against fatigue cracking is not a typical strength of WMA, one can guess that incorporating RAP into WMA may contribute to further reduce the performance achieved regarding that damage mechanism. Some authors [17] have reported problems for aged WMA produced with liquid additives, specifically in the case of Evotherm Dispersed Additive Technology and a specific surfactant.

The addition of RAP in WMA is expected to increase resistance to permanent deformation, as the WMA blends’ binder is likely to be stiffer [18,19].

In view of the expectations and the challenges concerning the use of RAP in WMA, it is necessary to learn more about WMA produced in the laboratory as well as in plant, with and without RAP, contributing to validate the technology. This paper presents and discusses the more relevant results obtained in a study involving the analysis of specimens produced in the laboratory and collected in trial sections constructed with commonly used laying and compaction equipment. Lowering of production and compaction temperatures was achieved by incorporating additives into the mixtures in the form of pellets. Some of the WMA blends were produced with incorporation of an organic wax, whereas some of others incorporated a chemical additive. In two blends the additives added were embedded in cellulose fibres.

2. Materials

2.1. Aggregates, RAP, bitumen and additives

A combination of three different fractions of limestone aggregate was used to produce all the blends in the study. In the first stage of the project, one HMA blend and six WMA compositions were studied in terms of their Marshall and volumetric properties. These compositions were produced in the laboratory to select the most promising to apply in the field. Based on the results obtained in the first stage, some of the blends were selected to be produced in plants and build the trial sections in real production circumstances. In addition, taking into account the laboratory study, a few blends suffered some adjustments prior to applying them in the field. The aggregate blends were determined based on a target grading Portuguese envelope for dense graded mixtures (AC 20 base). Fig. 1 illustrates the grading curves of the aggregate blends and RAP applied in the trial sections. Table 1 summarises other aggregate properties determined according to the Portuguese specifications.

All the blends were produced with conventional 35/50 paving grade bitumen, with a penetration, at 25 °C, of 45 × 0.1 mm, and a ring & ball softening point of 56 °C. The binder recovered from RAP had a penetration of 35 × 0.1 mm and a softening point of 52 °C. The average binder content of RAP was 4.2%.

Three different additives were used to allow reduction of handling temperatures of the WMA blends whose properties are presented in this paper: one organic wax (Sasobit®), one chemical additive (Rediset®), one chemical with cellulose fibres (Viatop® with Rediset®) and one organic wax with cellulose fibres (Viatop® CT40, containing Sasobit®). All these additives were added in the

Fig. 1. Grading curves of the aggregate blends and RAP (percentage by weight of material passing).
form of solid pellets. Table 2 summarises the properties of the different WMA additives used in this project. A complementary discussion on the main differences between them and the expected influence on WMA’s mechanical performance can be found elsewhere [3].

### 2.2. Compositions of blends

Although this paper focuses on the results obtained for the blends applied in real production conditions, a previous evaluation of similar blends was also carried out by testing Marshall specimens produced in the laboratory. Table 3 summarises information about the constituents and compositions of all those studied blends. The amount of additive added to the mixtures followed the suppliers’ recommendations. As shown in Table 3, there was a direct match between some of the laboratory mixtures and blends produced in the plant, such as M01 and M26, or M03 and M20. M21 and M24 were modified versions of M04 and M07, respectively, in which Sasobit and cellulosic fibres were used instead of Rediset and cellulosic fibres.

### 2.3. Production processes and handling temperatures

Initially, the production process and compaction of the WMA blends was established in the laboratory by moulding cylindrical specimens with (101.6 ± 0.1) mm. Mixing was carried out

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**Table 2**

Properties of the WMA additives used.

<table>
<thead>
<tr>
<th>Additive</th>
<th>Type</th>
<th>Generic composition</th>
<th>Characterisation</th>
<th>Recommended application rate</th>
<th>Temp. reduction (°C)</th>
<th>Melting point (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sasobit®</td>
<td>Organic</td>
<td>Fischer-Tropsch wax</td>
<td>Substance, solid saturated hydrocarbons</td>
<td>1–3% by weight of effective asphalt binder content</td>
<td>From 20 to 30</td>
<td>From 45 to 110</td>
</tr>
<tr>
<td>Rediset™</td>
<td>Chemical</td>
<td>Cationic surfactant + organic additive</td>
<td>Proprietary alkoxylated fatty polyamines</td>
<td>1–2% by weight of effective asphalt binder content</td>
<td>≥30</td>
<td>≥110</td>
</tr>
<tr>
<td>Viatop®</td>
<td>Mix CT40®</td>
<td>Fischer-Tropsch wax (40%) &amp; cellulose fibres (60%)</td>
<td>Substance, solid saturated hydrocarbons &amp; Polysaccharide</td>
<td>0.3–0.5% by weight of asphalt mixture</td>
<td>≥30</td>
<td>≥100</td>
</tr>
</tbody>
</table>

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**Table 3**

Composition of the studied blends.

<table>
<thead>
<tr>
<th>MATERIALS</th>
<th>LABORATORY eco-Warm Mix</th>
<th>TRIAL SECTIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>BITUMEN</td>
<td>35/50 paving grade bitumen content (%)</td>
<td>20 21 24 26</td>
</tr>
<tr>
<td>NATURAL AGGREGATES</td>
<td>4.5 4.5 4.5 4.5 3.2 3.2 3.5 4.5 4.5 3.5 4.5</td>
<td></td>
</tr>
<tr>
<td>Gravel 2: Limestone</td>
<td>● ● ● ● ● ● ● ● ● ● ● ●</td>
<td></td>
</tr>
<tr>
<td>Gravel 1: Limestone</td>
<td>● ● ● ● ● ● ● ● ● ● ● ●</td>
<td></td>
</tr>
<tr>
<td>Powder: Limestone</td>
<td>● ● ● ● ● ● ● ● ● ● ● ●</td>
<td></td>
</tr>
<tr>
<td>BY-PRODUCTS (%)</td>
<td>170302: Reclaimed Asphalt Pavement</td>
<td>- - - - - - - - - - - -</td>
</tr>
<tr>
<td>ADDITIVES (% of binder)</td>
<td>4.2 4.5 1.5 1.5 2 5 6 6</td>
<td></td>
</tr>
<tr>
<td>Organic: Sasobit®</td>
<td>4 4</td>
<td></td>
</tr>
<tr>
<td>Chemical: Rediset™</td>
<td>2 2</td>
<td></td>
</tr>
<tr>
<td>Mix additive: Rediset™</td>
<td>1.5 1.5 2</td>
<td></td>
</tr>
<tr>
<td>Viatop®</td>
<td>5 5 6 6</td>
<td></td>
</tr>
<tr>
<td>Viatop® + Sasobit</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Note:** Taking into account the amount of reclaimed bitumen introduced by RAP, the average binder content of M05, M06, M07 and M24 was 4.5%.
according to EN 12697-35 [21] and compaction was accomplished according to EN 12697-30 [22]. These samples were evaluated in what concerns some volumetric properties and then tested by the Marshall compression test. In a second stage, the blends that revealed better results for stability and flow in the Marshall compression test were produced in a batch plant and compacted with common asphalt compactors to validate real production conditions. This allowed collecting specimens for mechanical testing in the laboratory. Throughout the laying and compaction procedures practically no fumes were observed.

Taking into account the instructions from the additive producers and found in the literature [3], the WMA blends were prepared to a target temperature of 120 °C. For the HMA blends the target temperature was 165 °C.

In what concerns compaction in the laboratory, it was carried out at a temperature between 100 and 110 °C for the WMA mixtures and in the range of 120–150 °C for the HMA. In the field, the compaction process can be longer than in laboratory and also the existing conditions can cause a fast and considerable cooling of the material being compacted. In this project, all the trial sections were compacted in less than 45 min after laying, allowing compaction above the minimum temperature of 80 °C required for WMA applied. The conditions to build a layer thickness of 80 mm were favourable, with an air temperature around 25 °C and very low wind speed.

### 2.4. Marshall and volumetric properties of blends

The specimens moulded in the laboratory were submitted to Marshall compression tests to measure stability and flow. Volumetric properties such as porosity, voids in mineral aggregates (VMA) and voids filled with binder (VFB) were also evaluated. Stability and flow were determined for laboratory specimens only (M01 to M07) in the first stage of the study. Concerning the volumetric properties, they were also measured for the specimens cut from the trial sections (M20, M21, M24 and M26). Fig. 2 shows the average values obtained for those properties. Notice that similar blends produced in the laboratory and applied in real work conditions are represented side by side in each graph for better comparison.

Fig. 2 shows that the WMA blends M02, M03 and M04 yielded stability values below the minimum limit currently used in Portugal. In what concerns stability/flow ratio, only the blend M04 revealed a value below the minimum of 2 kN/mm typically required in Portugal for AC 20 base. As mentioned in Table 2, amongst these blends, no similar materials to M02 and M04 were applied in the field. The blends chosen to continue the study in real production conditions were selected by practical reasons as well as looking for better results in the performance evaluation framework. In terms of volumetric properties, with the exception of HMA (M01 and M26), the values obtained for specimens cut from...
the trial sections were similar to those of specimens moulded in the laboratory. The differences observed can be mainly attributed to compaction method (impact compaction) standardised for the Marshall method, which does not reproduce the field compaction method.

3. Performance evaluation

3.1. Production of specimens for testing

All the asphalt mixtures were produced in a batch plant, transported in lorries, spread with a common paver in the trial sections and compacted with tyre and metallic rollers.

Some slabs (with \(300 \times 400 \times 60 \text{mm}^3\)), cut from those trial sections’ pavements (according to EN 12697-27 [23]), were used in wheel-tracking tests and others were cut again to produce prismatic beams (with \(400 \times 55 \times 55 \text{mm}^3\)) to submit to four-point bending tests.

Cylindrical specimens were compacted in the laboratory (with loose mixtures collected during the trial sections execution) by the impact compactor in a Marshall mould prior to submission to indirect tensile tests.

3.2. Permanent deformation performance

The evaluation of permanent deformation resistance of the studied blends was performed by wheel-tracking (WT) tests according to EN 12697-22 [24]. The wheel of the WT passes over the specimen for 10,000 times, applying a contact stress of about 700 kPa. According to the applicable norm, after a rut depth of 20 mm is attained the tests finish even if the specified number of cycles was not achieved. Although the standard indicates a typical temperature of 60 °C to carry out the test, the representative temperature attained inside Portuguese pavements is 50 °C [25]. Therefore, the evaluation of permanent deformation resistance of the studied blends was carried out for both temperatures. Fig. 3 summarises the time-deformation curves (rut depth) obtained from WT tests. The obtained curves were used as the basis for determining the following parameters according to EN 12697-22 [24]: slope in air, \(\text{WTS}_{\text{AIR}}\), mean proportional rut depth, \(\text{PRD}_{\text{AIR}}\), and \(\text{RD}_{\text{AIR}}\). Fig. 4 illustrates the results of these parameters, measured at 50 and 60 °C, for the compositions applied in the trial sections. Table 4 shows the rankings obtained for the same compositions and specimens.

Generally speaking, M20 had the worst performance in terms of resistance to permanent deformation. Taking into account the results obtained in the Marshall method (Fig. 2) for M03, a weak performance of M20 could be anticipated. On the contrary, M26 was expected to exhibit good rutting resistance, since M01, the reference HMA studied in the laboratory, achieved good results for stability and flow in the Marshall tests. However, the level of porosity of M26 achieved in the field was too high, preventing this blend to perform better. Except for the additive used, M21 (with organic wax + cellulosic fibres) was quite similar to M04 (with chemical additive + cellulosic fibres) but the former resisted much better to permanent deformation. In what concerns M24 (with organic wax + cellulosic fibres + RAP), a good ranking could be anticipated taking into account the satisfactory results obtained for M07 in terms of stability and flow (Fig. 2). M07 and M24, both contained cellulosic fibres and RAP but the latter incorporated an organic wax instead of chemical additive.

The results show that introducing wax and cellulosic fibres into the mixtures M21 and M24 increased resistance to permanent deformation as compared to that of M20 (with chemical additive) and M26 (HMA). This indication is also confirmed by the poor performance in the Marshall test obtained for similar blends, M03 and M04, which were produced in the laboratory with chemical additives.

The two blends with higher resistance to rutting in WT tests, M21 and M24, incorporated a solid organic wax as additive and cellulosic fibres. M24 and M21 had similar compositions (in what concerns volumetric properties and binder content) but the former was produced with 35% by weight of RAP whereas the latter had no RAP. The presence of aged binder from RAP generally increases resistance of bituminous mixtures to rutting. Comparing performance of M24 and M21 in the WT tests, it was observed that introducing RAP practically did not change rutting performance. On the contrary, the results of Marshall tests revealed that M05 and M06 with RAP had higher stability and lower flow values than their reference blends, M02 and M03 produced with no RAP.

As shown in Fig. 4, M20, produced with a chemical additive, revealed excessive susceptibility to temperature increase from 50 to 60 °C.

3.3. Stiffness modulus results

The evaluation of stiffness modulus and phase angle of the studied mixtures was performed according to EN 12697-26 [26] in four-point bending tests. The testing machine has a clamping device that allows free rotation and translation at the reaction points.

Prismatic beams were tested using repetitive four-point bending tests, carried out under controlled strain conditions (strain levels of 50 and 150 \(\mu\text{m/m}\)) at 20 °C. A sinusoidal wave loading was applied at six frequencies (30, 20, 10, 5, 3 and 1 Hz). Fig. 5 displays the obtained stiffness modulus and phase angle results for the strain level of 50 \(\mu\text{m/m}\) and error bars indicating one standard deviation. The strain level slightly influenced response of the material, resulting in a slight decrease in stiffness moduli and a small increase in phase angles as the strain level increased, as shown in Fig. 6 for the frequency of 10 Hz.

The blend M24 (with RAP + wax and cellulosic fibres) showed consistently lower stiffness modulus (around 25% less at 10 Hz) as compared with the warm mixtures without RAP. However, the values measured for the phase angle of M24 are at the same level...
(differences around 10% for 10 Hz) of those obtained for the blends without RAP. This indicates that the viscous component of WMA with RAP seems to have low significance.

A supplementary exploration of the stiffness results was carried out through linear multivariate regression analysis. The statistical evaluation was carried out with SPSS – Statistical Package for the
Social Sciences – in order to verify the assumptions of application of regression analysis and to obtain the best-fit models (higher adjusted $R^2$) based on the independent variables determined in the laboratory. Stiffness modulus ($E$) was considered as the dependent variable whereas loading frequency ($f$ in Hz), porosity ($V_m$ in%) and strain level ($e$ in $\mu$m/m) were used as independent variables as they were statistically significant and led to the best fit models [expression (1)]. Notice that experimental porosity values used to derive the regression models varied from 4 to 8%, approximately.

$$\log E = a \times \log f + b \times V_m + c \times \log e + d$$

(1)

Table 5 summarises the values derived for the coefficients $a$, $b$, $c$ and $d$ as well as the adjusted $R^2$. The first two lines of the table show mixtures combined by type of aggregate whereas the third line displays a combination of blends by type of additive. The combination in the same model of a WMA blend without RAP (M21) with other with RAP (M24) led to a lower adjusted $R^2$ (69.9%), showing that response of those two WMA to loading seems to be quite different.

The evolution of stiffness moduli, calculated with Eq. (1), can be observed in Fig. 7 as a function of loading frequency for the range of porosity variation measured on the specimens submitted to testing, and also as a function of the strain levels applied.

As expected and illustrated in Fig. 7, the predicted values for stiffness modulus of the blends M20 and M21, both WMA without any RAP, are quite influenced by porosity. A variation of this property in the proper range of values for AC 20 base (from 4 to 8%) is likely to induce a reduction in stiffness modulus at 20 °C of about 26% for the WMA blends without RAP. In the case of M24, which incorporate 35% of RAP, the same variation of porosity is expected to reduce stiffness in 61%.

### 3.4. Resistance to fatigue

The test carried out in this study to evaluate fatigue behaviour was a four-point bending test, analogous to the one described for stiffness, according to EN 12697-24 [27]. The chosen fatigue resistance criterion was 50% loss of the initial stiffness modulus. The loading form was a sine wave with a frequency of 10 Hz, applied for three different strain levels (150, 250 and 350 $\mu$m/m) at 20 °C. According to EN 12697-24 [27], the fatigue performance of each mixture (N) was obtained from eighteen specimens (with a cross section of $55 \times 55$ mm$^2$), six per strain level. Fig. 8 shows the blend’s average fatigue performance measured in the laboratory.

The specimen’s dimensions apparently contributes to individual fatigue results with some variability, once the type of blends studied have a relatively low amount of mastic and the maximum dimension of aggregate is 20 mm. Although the performance observed for all the mixtures is not very different, M24 revealed better fatigue performance.

Another way of interpretation of fatigue performance is by deriving fatigue laws. The fatigue laws ($e = a \times N^b$) and the determination coefficient ($R^2$) obtained from prismatic beams extracted from the trial sections are shown in Table 6. For comparison, the $e_0$ parameter (strain which induces specimen decay after 1 million load cycles) was also calculated from the fatigue laws obtained by regression analysis.

Again, the results indicate that all the studied blends have similar fatigue performance. The difference between the observed fatigue performance of M24, which is the blend that showed best performance, and M21 is only 12%. Therefore, this confirms that the WMA blends tested have similar fatigue performance amongst them and they are also comparable with the performance of HMA (M26).

Additionally, the results of fatigue tests were also examined based on a regression analysis by considering three independent variables ($E$: stiffness modulus; $V_m$: porosity; N: number of load repetitions), in accordance with Eq. (2). Statistical analysis was carried out as described in Section 3.3, now for the results of fatigue resistance.

$$\log e = a \times \log E + b \times V_m + c \times \log N + d$$

(2)
Models based on Eq. (2) were developed individually for all the blends and for some combination of them. However, $E$ and $V_m$ were not statistically significant and, consequently, for these situations the models were disregarded.

Table 7 summarises the values derived for the coefficients $a$, $b$, $c$ and $d$ as well as the adjusted $R^2$ and Fig. 9 represents the expected fatigue performance of M20 and M21, as a function of stiffness modulus and porosity. The results allow anticipating a considerable reduction in fatigue performance of this type of WMA blends as stiffness modulus and porosity increases. Considering, for instance M20, a typical stiffness modulus at 20 °C between 4000 and 5000 MPa, fatigue life is expected to suffer a variation from 1.5 to 2.25-fold around the mean when porosity varies from 4 to 8%.

### 3.5. Water sensitivity

As mentioned above, water sensitivity is generally a weak point of WMA. Therefore, the evaluation of moisture susceptibility is indispensable in the characterisation process of WMA. In this project, ITSR – Indirect tensile strength ratio was selected to evaluate...
water sensitivity, according to the procedures indicated in EN 12697-12 and EN 12697-23.

Six specimens with (100 ± 3) mm in diameter, moulded and compacted in the laboratory, were tested for each blend. Three of them are conditioned in water at (40 ± 1)°C for 68–72 h. Then this set of specimens is submitted to a conditioning procedure at (15 ± 1)°C for a time greater than or equal to 2 h. Afterwards, indirect tensile strength (ITS) is measured in diametrical load compression tests. ITSR is the percentage of ITS obtained for the set of conditioned specimens (ITS_w) as compared to ITS measured to the dry group of specimens (ITS_d), which is not submitted to the conditioning procedure. Fig. 10 presents the obtained results for the studied blends.

The results show that ITSR achieved 93.1% for the HMA (M26). All the WMA showed good performance in terms of water sensitivity as all the values of ITSR are above 80%. Although M24 incorporated RAP, the same good behaviour was observed for this blend. Although there was some concern related with water sensitivity of WMA, for the additives and production temperatures used for the studied blends, no weaknesses were observed regarding susceptibility to moisture.

3.6. Global analysis and discussion of results

Generally speaking, the results show that mechanical performance of the WMA blends applied in the trial sections was satisfactory and generally similar or even better than that of the conventional HMA used as a reference. This was also observed for the specific WMA with wax and cellulosic fibres, and 35% of RAP.

In order to show the relative performance of the studied blends, some results were collected from the literature and are presented below (Fig. 11).

As observed in Fig. 11, most of the blends developed a rut depth between 1 and 7 mm. In this study, only M20 did not satisfy that deformation level for the test carried out at 60°C, possibly because the testing temperature was above the bitumen’s softening point. The chart displayed on the right, which relates WTS_AIR and RD_AIR,
confirms that amongst WMA blends only M20 revealed higher permanent deformation than the others. All the displayed blends, WMA and HMA, are within a region limited by values of WTS\_AIR and RD\_AIR of 0.4 mm/10^3 cycles and 7 mm, respectively.

The available information mentioned in the studies allows verifying that the results have generally great variation, and the contribution of recycled aggregates and additives for rutting performance is unclear. Therefore, the choice of an additive will depend on actual performance derived from mix design studies, regardless of preconceived ideas on the expected behaviour of a blend with a specific additive.

In the case of M24, which incorporated RAP, any further evaluation on actual binder content was carried out. However, some segregation in RAP is likely to occur. This is difficult to avoid in real production conditions, leading to some variation in binder content of specimens submitted to testing. As a consequence, as observed for M24, stiffness modulus was somewhat lower and fatigue performance was slightly better than the observed for the other WMA under evaluation. It seems that the possible higher binder content in M24 did not reduce rutting resistance because this blend had harder bitumen from RAP and organic wax as warm additive.

The comparison of results displayed in Fig. 12 allows looking at fatigue performance in a more general perspective. The graph shows M26 (HMA) as a reference mixture to assess fatigue performances of the WMA blends tested in this study as well as others.
evaluated elsewhere. Higher ordinate, $e$, and higher abscissa values, $b$ (fatigue law exponent), identify better fatigue performance. Thus, the blends with higher fatigue resistance are located in the upper right quadrant. As shown in Fig. 12, most WMA blends are positioned in the bottom right quadrant. This means they exhibited lower fatigue performance than M26 considering $e$ as the evaluation parameter. However, the slopes of the WMA blends’ fatigue laws were also lower (i.e., exponents of fatigue laws are higher) and, hence, the expected number of admissible loading cycles was higher for these mixtures.

Generally speaking, WMA with RAP presented a tendency to perform better to fatigue than the other WMA blends. There is no evidence that WMA tends to perform worse than HMA with similar volumetric composition.

This study confirms the convenience of having a process to rank, somehow, several WMA blends produced with different additives and/or incorporating diverse percentages of RAP. Therefore, based on mechanical performance measured in the laboratory, a simple procedure is proposed to help rank the blends. In all, six parameters were considered to rank the blends: $RD_{\text{Air}}$, $WS_{\text{Air}}$, $E$, phase angle ($\phi$), $e$, and ITSR. Each of these parameters was weighted to balance their contributions for a global performance indicator, which is somehow subjective, representing the authors’ perspective regarding the suitable properties for a blend used in base and binder layers: $RD_{\text{Air}}$ 15%; $WS_{\text{Air}}$ 15%; $E$ 20%; $\phi$ 5%; $e$ 40%; ITSR 5%. The first step involves normalisation of each parameter, i.e., representing it in a scale from 0 to 100%, dividing each individual value by the maximum of them.

Fig. 13 shows the ranking of the studied blends considering the mentioned weights and the normalised values. This global analysis shows that M21 was the best blend. All of the others revealed a performance approximately at the same level.

4. Conclusions

The research study presented in this paper focuses on the mechanical characterisation of warm-mix asphalt concrete to be applied in base or binder layers. In a first stage, a preliminary evaluation of the blends’ volumetric properties and Marshall stability and flow was carried out to find the most promising compositions to apply in the trial sections built in real production conditions. One HMA blend was also studied as a reference mixture. One of the WMA blends incorporated 35% of RAP and four different warm additives were used: a chemical additive, an organic wax, an organic wax associated with cellulosic fibres, and a chemical additive allied to cellulosic fibres. The specimens collected from the field allowed the development of a mechanical characterisation program in the laboratory.

Based on the results as well as on the information collected in the literature, the following conclusions can be derived from this study:

- The performance evaluation of WMA that incorporated 35% of RAP led to satisfactory results, but a close control of the blend’s grading curve and the amount of binder added by the RAP is recommendable to avoid heterogeneity throughout the production process.
- Taking into account the real values of porosity achieved after laying the mixtures in the trial sections, a significant variation of stiffness and resistance to fatigue could be anticipated, leading to the alert that construction and compaction conditions should be very well set and implemented in order to avoid very different porosities when compared with the mix design study.
- In what concerns sensitivity to moisture, the studied WMA revealed a suitable performance in the range of production temperatures used, notwithstanding some problems associated with moisture have been reported in the literature when aggregates are not appropriately dried; the use of adhesion agents is recommended when using production temperatures in the lower level recommended for WMA.
- The blends produced with organic wax yielded slightly higher stiffness modulus than similar mixtures with chemical additives.
- A slight decreasing in stiffness modulus for M24, which incorporated 35% of RAP, was probably originated by a supposed higher binder content, associated to some segregation on the RAP grading (more fines than expected).
- The supposed higher binder percentage of M24 is likely to justify good fatigue performance of this WMA with RAP as well as a slightly lower performance to permanent deformation than M21 produced with the same additive.

Finally, the activities performed throughout this study have shown that WMA produced with a high RAP percentage is feasible, contributing to reduce energy consumption and costs. The study also demonstrates that mechanical performance of that type of blends is satisfactorily and, therefore, solutions based on WMA with RAP can be seen as a suitable alternative to conventional HMA for base and binder layers of roads’ pavements.

References
